

Enhancing the circular economy with nature-based solutions in the built urban environment: green building materials, systems and sites

David Pearlmutter^{a,*}, Dimitra Theochari^b, Thomas Nehls^c, Pedro Pinho^d, Patrizia Piro^e, Alisa Korolova^f, Spiros Papaefthimiou^g, Mari Carmen Garcia Mateo^h, Cristina Calheirosⁱ, Irene Zluwa^j, Ulrike Pitha^j, Paul Schosseler^k, Yaakov Florentin^l, Shahar Ouannou^l, Erez Gal^m, Andreas Aicherⁿ, Killian Arnold^o, Erika Igondová^p and Bernhard Pucher^q

^a Department of Geography and Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Beer Sheva, Israel

^b Ramboll Studio Dreiseitl/ MSB Landschaftsarchitekten; PhD Cand, National Technical University of Athens, Stournari and Patision, 42 35, Athina 106 82, Greece

^c Center for Innovation and Science on Building Greening (CIBG) Chair for Ecohydrology, Institute of Ecology Technische Universitaet, Berlin, Germany

^d cE3c-Centre for Ecology, Evolution and Environmental Changes, Faculdade de Ciências da Universidade de Lisboa, Portugal

^e Department of Civil Engineering, University of Calabria, Italy

^f Faculty of Architecture, Riga Technical University, Latvia

^g School of Production Engineering & Management, Technical University of Crete, Greece

^h MCG Research & Innovation Sustainability Architecture/Urban Planning, Spain

ⁱ Interdisciplinary Centre of Marine and Environmental Research (CIIMAR/CIMAR), University of Porto, Portugal

^j Institute of Soil Bioengineering and Landscape Construction, University of Natural Resources and Life Sciences Vienna (BOKU), Austria

^k PositivImpaKT Solarwind Windhof, Luxembourg

^l Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Israel

^m Department of Structural Engineering, Ben-Gurion University of the Negev, Israel

ⁿ Urban Water Management and Sanitation, Bauhaus Institute for Infrastructure Solutions, Bauhaus Universitaet Weimar, Germany

^o Engineering and Architecture, Lucerne University of Applied Sciences and Arts, Switzerland

^p Department of Urban Planning, The Municipality of the Capital City of Bratislava, Slovakia

^q Institute of Sanitary Engineering and Water Pollution Control, University of Natural Resources and Life Sciences Vienna (BOKU), Austria

*Corresponding author. E-mail: davidp@bgu.ac.il

Abstract

The objective of this review paper is to survey the state of the art on nature-based solutions (NBS) in the built environment, which can contribute to a circular economy (CE) and counter the negative impacts of urbanization

This is an Open Access article distributed under the terms of the Creative Commons Attribution Licence (CC BY-NC-ND 4.0), which permits copying and redistribution for non-commercial purposes with no derivatives, provided the original work is properly cited (<http://creativecommons.org/licenses/by-nc-nd/4.0/>)

through the provision of ecosystem services. NBS are discussed here at three different levels: (i) green building materials, including biocomposites with plant-based aggregates; (ii) green building systems, employed for the greening of buildings by incorporating vegetation in their envelope; and (iii) green building sites, emphasizing the value of vegetated open spaces and water-sensitive urban design. After introducing the central concepts of NBS and CE as they are manifested in the built environment, we examine the impacts of urban development and the historical use of materials, systems and sites which can offer solutions to these problems. In the central section of the paper we present a series of case studies illustrating the development and implementation of such solutions in recent years. Finally, in a brief critical analysis we look at the ecosystem services and disservices provided by NBS in the built environment, and examine the policy instruments which can be leveraged to promote them in the most effective manner – facilitating the future transition to fully circular cities.

Key words: built environment, circular economy, nature-based solutions

INTRODUCTION

As defined by [Langergraber *et al.* \(2019\)](#), nature-based solutions (NBS) are concepts that bring nature into cities – and in many cases this includes ideas for urban design that are inspired or derived from nature. Thus while NBS may be considered more generally as actions which protect, sustainably manage, and restore natural or modified ecosystems ([IUCN 2019](#)), the specific focus here is on the implementation of NBS within *urban* ecosystems.

Even within cities, NBS contribute to global objectives such as climate change mitigation and adaptation, and they have the potential to enhance human wellbeing biodiversity and resource recovery. All of these goals find expression in the design of buildings and urban spaces, or what is commonly referred to as the ‘built environment’. Over the last 15 years, in fact, the concept of NBS has come to encompass design solutions for contemporary landscapes and architecture, in which natural and living material – as well as policies, measures and actions promoting their use – are leveraged to meet specific societal challenges that are pervasive in the built environment.

One example of a societal challenge that may addressed using NBS is the urban heat island effect (UHI), by which temperatures in cities are increasingly higher than in surrounding areas – exacerbating heat stress for vulnerable urban populations. In temperate climates this risk is highest during the night time, and mainly indoors ([Buchin *et al.* 2016](#)). Among UHI countermeasures, urban green space is considered among the most effective for reducing air temperatures outdoors, but for addressing the indoor hazard it is most effective to apply measures at the building level – highlighting the fact that NBS must be implemented at a range of scales in order to deliver the optimum benefit ([Saaroni *et al.* 2018](#)).

The ubiquitous grey infrastructure in cities – consisting of impervious paving, buildings, and other structures – contributes as a whole to the worsening of the urban climate through a lack of resilience and flexibility. Thus the importance of urban green infrastructure (GI) is related to the amelioration of social stresses, which are intertwined with physical phenomena in cities. Contemporary issues related to grey infrastructure include its ageing and the need for maintenance, along with the worldwide recognition that conventional infrastructure solutions are often insufficient and ineffective. The inclusion of NBS in new and innovative strategies can address such issues as water quality while simultaneously delivering additional benefits. These benefits are vital to promote aspects of sustainable development presented in a 2018 United Nations report which states that ‘...upscaling (of) NBS will be central to achieving the 2030 Agenda for Sustainable Development’ ([WWAP 2018](#)).

Another important aspect when approaching contemporary urban systems is ‘circularity’.

Circular economy (CE) is an evolving ‘umbrella’ concept embodying internal complexities and multiple definitions, but is defined here ([Langergraber *et al.* 2019](#)) as an economic system that

aims at minimising waste and making the most of resources. In a circular system, resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing energy and material loops. According to Prieto-Sandoval *et al.* (2018), 'this concept represents a change of paradigm in the way that human society is interrelated with nature and aims to prevent the depletion of resources and facilitate sustainable development through its implementation at the micro (enterprises and consumers), meso (economic agents integrated in symbiosis) and macro (city, regions and governments) levels. Attaining this circular model requires cyclical and regenerative environmental innovations in the way society legislates, produces and consumes.'

Moreover, cities are composed of multiple overlapping infrastructure systems, while at the same time become the spaces where people develop social experiences and cultural values. Urban quality is a target for cities that are competing against each other to attract the most valuable and entrepreneurial citizens. A great number of theories, manifestos and city guidelines have been developed in cities of the world to promote new urban qualities and citizen wellbeing. Frederick Law Olmsted argued that '...the enjoyment of scenery employs the mind without fatigue and yet exercises it, tranquilizes it and yet enlivens it; and thus, through the influence of the mind over the body, gives the effect of refreshing rest and reinvigoration to the whole system' (Olmsted 1865).

One of the central concepts underlying NBS which has been recognized for several decades by the scientific and design communities, and intuitively for hundreds of years by the population at large, is *biophilia* – defined as the 'innate human attraction to nature'. Biophilic design is of growing interest within architectural theory and practice, due to published research showing that design which increases the exposure and direct connection of people with the natural world 'can reduce stress, improve cognitive function and creativity, improve our well-being and expedite healing' (Browning *et al.* 2014). Social life and culture develop constantly in the city context and their relation to nature and new green infrastructure solutions is a very important goal for NBS.

Against this background, the aim of this review paper is to survey the state of the art on integrating NBS in the built environment, which can counter the negative impacts of urbanization and contribute to a circular economy through the provision of ecosystem services. We approach this review at three scales of implementation, those of building *materials*, *systems*, and *sites* (Figure 1) – which, as defined below, constitute the focus of the paper.

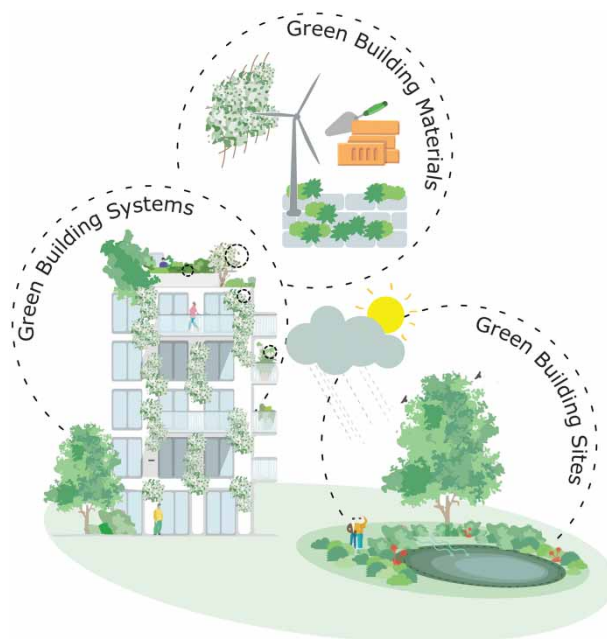


Figure 1 | Three scales of NBS implementation in the built environment: green building materials, systems for the greening of buildings, and green urban sites. Illustration: Dimitra Theochari (unauthorized use is not permitted).

Green building materials are raw and processed nature-based materials used in the construction of the built environment. These materials are extracted from the biological cycle to serve technical purposes, and their production and processing should result in low environmental impacts in terms of measures such as embodied energy and carbon, water consumption and the use of harmful chemicals. Ideally, they make productive reuse of other resource streams to avoid detrimental by-products and competition with food production, and they guarantee a healthy working and living environment with respect to indoor air quality and climate. The material processing and construction techniques should ideally be such that nutrients can be safely returned to the ecosystem at the end of the use cycle of the building material.

Green building systems in this context are systems for the greening of buildings, and include components such as green roofs, façade greenery and living walls, house trees, and even building-integrated constructed wetlands. Green roofs are designed with either intensive or extensive planting: an intensive green roof is supplied with water and nutrients and its substrate is usually thicker than 0.25 m, while an extensive green roof is not irrigated and has a much shallower substrate, usually 0.06–0.15 m. Façade greenery consists of climbers or climbers rooting in soil or artificial substrates, directly attaching to the wall surface or covering the wall indirectly through support systems like trellises or ropes. Since the plants use other structures to develop, they do not have to invest in their own static apparatus – an evolutionary adaptation that often allows them to grow much faster than trees (e.g. *Fallopia baldshuanica* reaches up to 12 m in height in just one growing season).

Green building sites may be open spaces directly adjacent to buildings, typically within in the same property, or land parcels of small and medium scale (pocket parks, urban plazas, small community parks, elevated urban green promenades) that have a role in the blue-green (i.e. water and vegetation-based) network of the city. Green building sites are spaces for establishing nature in cities, enhancing biodiversity through blue-green infrastructure components, providing opportunities for biophilic design and promoting culture and social life through activities for diverse social and age groups. Ideally green building sites provide multiple ecosystem services, and embody resilient and regenerative ways to deal simultaneously with challenges ranging from climate change mitigation to the reduction of noise pollution. They may increase flood safety through integrated water sensitive urban design (WSUD) solutions, improve air quality, reuse site material while reducing construction waste, use construction materials that are permeable and sustainable, promote local economic systems, and maintain low life cycle impacts. The intent of NBS at the green building sites scale is to promote sustainability goals, outdoor comfort, healthy living environments and wellbeing in cities.

NBS IN THE BUILT ENVIRONMENT: PROBLEMS AND SOLUTIONS

Meeting the challenges posed by urbanization and the growth of cities has a pivotal role to play in the transition of society to a circular economy (CE). These challenges derive from a wide variety of environmental impacts associated with the production of building materials, the operation of buildings and their allied systems, and the outdoor processes which take place within the built-up area (Elmqvist *et al.* 2013). In this section we first summarize these impacts, and then survey the historical use of nature-based solutions that can be leveraged in the future to minimize their negative consequences.

Impacts of the built environment on people and natural systems

In Europe, energy use in residential and commercial buildings accounts for over 40% of the total end-use consumption (Enerdata 2012), making buildings the largest energy-consuming sector and a major emitter of greenhouse gases (GHG). However, this proportion refers only to ‘operational’ energy use,

or that which is consumed for heating, cooling, ventilation, and otherwise making the building habitable and supporting the ongoing needs of its occupants. Additional energy consumption and related GHG emissions are attributable to the production of the building and its constituent materials, and to the characteristics of urban open spaces – in which microclimatic and other processes crucially influence the dependence of people on energy-intensive buildings and urban transport. Therefore, the design of the built environment has a determinative impact not only on the quality of contemporary urban life, but also on society's long-term contribution to anthropogenic climate change and natural resource depletion (Kabisch *et al.* 2017).

Building material production

Most modern building materials are produced using processes that rely heavily on non-renewable resources, generate large quantities of waste, and potentially create unhealthy surroundings. The most ubiquitous of these materials is concrete, which may be either cast on site or used to manufacture pre-cast elements like wall blocks, and whose key active ingredient is Portland cement. Cement has an extremely high level of embodied energy in its production, and is a major source of GHG emissions (Huberman *et al.* 2015). This is because vast quantities of carbon dioxide are released to the atmosphere as part of the calcination process in which natural limestone and other raw materials are converted into clinker (the key ingredient in cement), and additional CO₂ is emitted due to the combustion of fossil fuel for producing the required temperature of approximately 1,500 °C. Because of such high-temperature production processes, many other modern materials have high embodied energy as well. These include the reinforcing used in structural concrete (especially when it is virgin steel produced from iron ore, rather than recycled from scrap), and even materials that are increasingly employed for thermal energy efficiency – such as aluminium and glass for high-performance windows, and petrochemical-based plastics such as expanded polystyrene for thermal insulation. Beyond embodied energy and carbon emissions, a host of direct and indirect offsite environmental impacts (such as air pollution and water contamination) are also incurred through the extraction of minerals from mines and quarries, and the long-distance transport of both raw materials and finished products.

The building and its operational systems

Buildings provide people with shelter from cold, heat, wind and precipitation, but also have negative impacts on organisms and ecosystems. Among the direct impacts are the reduction of vegetation and disconnection of habitats on the ground, as buildings seal the soil and thus disrupt the cycles of water, gases, nutrients and energy. On building roofs, rainwater is concentrated in volume and time, and about 85% is typically directed to drainage where it infiltrates directly into the ground or into sewers – bypassing soils, plants and the atmosphere. Buildings impact the urban surface roughness and turbulent exchanges of heat and pollutants, often trapping them in streets and other occupied spaces. Compared to a vegetated surface, buildings also increase the absorptive surface and the heat storage capacity by accumulation of high density, high heat capacity materials, which leads to longwave radiation emission during the night and the formation of urban heat islands – contributing to heat stress both indoors and outdoors. In cold northern climates, densely packed buildings can block sunlight to an undesirable extent in terms of both health and potential passive solar heating.

Because urban populations spend the large majority of their time indoors, their consumption of water, materials and energy – and their production of wastewater, waste and excess (anthropogenic) heat – are concentrated within buildings. Biological primary production is reduced to a minimum, as food is imported, processed and consumed, with residues and waste flushed into the sewer

system – again bypassing the soil (where these organic materials are usually decomposed and mineralized) and the vegetation (which is usually taking up the corresponding nutrients). Heating and cooling in homes, businesses and industry consume around half of the energy produced in the EU (Enerdata 2012), and buildings are projected to remain the largest energy-use sector worldwide, even under future decarbonisation scenarios (US EIA 2017).

Outdoor processes in building sites

Urban spaces, typically covered by hard paving using materials like concrete and asphalt, can create environmental problems both within and beyond their boundaries. Without shade from trees, such spaces exacerbate thermally stressful microclimatic conditions on hot days and discourage pedestrian activity – which can in turn increase the reliance of city dwellers on air-conditioned vehicles and indoor spaces. When the albedo of unplanted ground surfaces is low, their surface temperature may reach extreme levels, and when it is high they expose users to reflected solar radiation which increases visual as well as thermal stress. Hydrologically, large areas of impervious paving contribute to surface runoff that may lead to soil erosion, impaired water quality and the risk of flooding.

These sites also diminish biodiversity, by creating a harsh environment for wildlife. The strongest impact comes from direct habitat destruction, when existing green spaces are replaced by buildings and roads. Remaining habitats, as well as newly built ones, also face challenges, mostly related to habitat fragmentation. Green spaces in cities can be viewed as islands isolated by a hostile environment, and thus species present must cope with different abiotic pressures, e.g. from increased air pollution (mostly from vehicles), altered microclimate (related to the urban heat-island effect) and isolation (which limits species dispersion between green spaces). Also, the biotic interactions between species are affected due to the presence of exotic and invasive species, and the prevalence of disturbances stemming from human activities, such as noise pollution.

Historical overview of NBS in the built environment

Traditional building materials and techniques

The use of ‘nature-based solutions’ in the built environment is not a new phenomenon, as builders throughout history have employed materials and techniques enabled by the natural surroundings. Indigenous architecture around the world is characterized by buildings that were constructed from local materials and often displayed a remarkable unity with their environment (Blaser 1982). By using locally available resources in ways that respond to local conditions, traditional building practice has led to the evolution of distinct regional building types. Prominent examples vary from domed igloos built of ice and snow in arctic regions to solid earth construction (cob, rammed earth, mud bricks) without an interior skeleton structure, as can be seen in adobe Pueblos of the arid American southwest (Lehner 2016). Natural stone is among the most important building materials due to its strength and durability, either forming whole huts (Italian Trulli or Bories in the Provence) or building up houses with thick stone walls supporting a turf roof with living grass sod (Blaser 1982). As detailed below, living plant material was also used to form ficus tree bridges in India (Rodgers 2019).

More common than living plant material is the use of harvested material, in a wide range of construction types from the compact wooden architecture of Europe to light bamboo piles in Asia. Tipis of the Great Plains and yurts of Central Asia exemplify skeleton structures of wood or other plant material covered by tensile fabrics of plant-fiber or animal skins. The Hawaiian hale consists of a more complex skeleton structure system, containing a ridge purlin and different junctions, covered with plant leaves. In the Nile Valley of Egypt, typical dwellings were constructed using an inner structure made of wooden poles, reeds or wickerwork, covered by a layer of mud. Another

plant-based material typical for eastern construction is paper, used for Japanese shoji doors or fusuma screens (Brown 2012).

The use of wood in construction traditionally reflects the proximity of forests and the availability of tree species with given properties. In areas such as northern Europe that are rich in trees with hard and solid stems, heavy timber walls and snow-bearing pitched roofs with wooden planks have been historically pervasive – though today they have largely disappeared from many regions due to the high price of wood. In areas where forest trees yield thinner and shorter trunks, there is a more common use of lighter wood-frame walls filled with other materials such as brick, and where timber is scarce, soil is often used as a construction material, together with light wood and reed. In stony-karst (e.g. Mediterranean coast and mountain) areas, stone construction is dominant – and in 2018 the art of dry-stone walling in countries such as France, Greece, Italy, Croatia and Spain was acknowledged by UNESCO to represent an intangible contribution to the cultural heritage of humanity.

A number of properties commonly found in indigenous architecture can be instructive for the future implementation of NBS (see overview of traditional materials in Table 1):

- Material is sourced from local vegetation or geological deposits (Heringer 2012).
- Reliance on non-renewable energy resources is low (Heringer 2012).
- Building form is thermally and structurally adapted to climate (Pearlmutter 2007).
- Durability is enhanced by regular maintenance (Georgi-Thomas & Zeumer 2012).
- Buildings are simple in construction and the materials are recyclable and compatible with biological cycles (Sauer 2012).

Building greening systems that are integrated with user lifestyles

Vegetation has always played an important role in the direct surroundings of houses. Living green plants symbolize life, health and prosperity – and have provided countless advantages to the inhabitants.

Trees planted directly next to the house are a regular feature of settlements in Europe (Wieland 1983). In central Europe, common species include Oak (*Quercus* spp.), Lime (*Tilia platyphyllos*), Ash (*Fraxinus excelsior*), Pear (*Pyrus* spp.) and Apple (*Malus domestica*). In southern Europe *Magnolia spec.*, *Acer* spp., *Olea europaea*, and Palm trees (*Palmae*) have been common, as has *Platanus* in western Europe. Trees have been appreciated for their aesthetic value as they indicate the seasons by flowers and colorful foliage. They also structure the direct surroundings of houses through shadow and light patterns, and deciduous trees selectively cast shadow in the summer and let the light pass during winter. Different species provide fruit, pharmaceuticals, fodder, and valuable wood, and attract insects for pollination. Trees have often carried a high cultural and mystic-religious importance as well. Nowadays, in spectacular cases such as the ‘Hundertwasser Haus’ in Vienna (Austria) or the ‘Bosco Verticale’ in Milano (Italy) trees are brought into and onto houses (Figure 2). At the same time, the appreciation for ordinary, traditional house trees and street trees is decreasing, as dwellers think they have less need for the trees’ services. The work in gardens and the surroundings of houses has been outsourced (like in the Bosco Verticale) and for municipalities, maintenance costs and safety seem to be most important aspects (O’Sullivan *et al.* 2017). For instance, in Berlin, the number of street trees planted yearly decreased from over 8,000 in 1992 to just over 2,000 in 2018 – while the number of trees cut varied around a mean of around 4,800 per year (SenUVK Berlin 2019). This development, together with pests and diseases like ash dieback, Dutch elm disease (Jernelöv 2017), or the *Ceratocystis platani* and *Massaria* disease of *Platanus* species, are decreasing the number of house and street trees across Europe (Schmitt *et al.* 2014).

Table 1 | Traditional building materials and their relevant properties for implementation of NBS

Source	Material	Uses	Recyclable/reusable	Renewable	Environmental impact
Animals	wool/hair	blankets, carpets, textiles for insulation and shading	can be reused/reshaped or be used as an additive	yes (grows on animals)	CO ₂ – impact of animal production (but could be a side product of food production)
	leather/pelt dung	additive in clay or concrete tipi/yurt coverage floor, ground material additive in clay or concrete	not reusable because bound in material depending on process of dressing can be composted or burned once dried out not easy to reuse, but can be returned to soil	yes yes (animal waste product)	
Plants	living plant material	sod for roofing climbers/clingers/creepers for bridges & sunscreens	can be composted or burned at end of life	yes	binding of CO ₂ , habitat function
	wood	large-dimension timber & poles for primary structure boards and planks scantling, smaller pieces, shingles	can be reused/reshaped repeatedly if not chemically treated, and composted or burned at end of life	yes, but careful management needed yes	binding of CO ₂ during growth phase/harvesting, transport and production process creates positive or negative energy balance
	cork/bark	insulation material, flooring	can be reused or recycled	yes, but careful management needed	
	bamboo	roof structure, walls, fences, decoration	yes, but usually weak after initial use, can be composted or burned	yes, rapidly	water/energy demand depending on production process, various chemicals added
	rush, straw, thatch	roofs & ropes	can be composted	yes, rapidly	
	hemp	thermal insulation	yes	yes	
Earth	paper	walls and screens wallpaper	can be reused or recycled no (sticky glue on it)	yes partly	
	water	ice buildings	can be reused or recycled	no	low
	mud/clay	component in clay or concrete	no		moderate?
		walls, floors, stoves	once dried out not easy to reuse, but can be returned to soil		low
		bricks	after firing not easily reusable, but can be returned to soil		average, depending on energy resource for firing
	stone	tiles (glazed material)	reusable but not easily recyclable		depending on energy resource for firing and glazing
		plaster	can be reused, recycled as gravel		depending on mining process and transport
		walls	can be reused, recycled as gravel		
	sand	gravel	can be recycled in concrete		
		glass	can be recycled		depending on mining process, transport and energy resource for production
	metal	various products	can be reused or recycled		
	lime	paint	can be returned to soil with other products		
	<i>opus caementicium</i> (lime and sand)	walls, floors, roofs	can be recycled in concrete		



Figure 2 | Examples of building integrated trees. Left: gardeners in front of Bosco Verticale in Milano, Italy and right: the Hundertwasser Haus in Vienna, Austria (photos: Thomas Nehls).

Façade greening is the melding of the artificial constructed and the naturally grown. There are very old examples for climbers and vines which were used to green buildings like the legendary hanging gardens of Semiramis and the shade creating wine-pergolas of Roman villas (Gothein 1926). Useful climbers and vines might have always been brought near houses and might have greened buildings and walls. *Hedera helix* is one of the most prominent examples, described in antiquity by Hippocrates of Kos (460–370 BC) and Pliny the Elder (23–79 AD) and in historical times as well (Turner 1538). In central Europe it has been used as a garden plant at least from the middle of the 16th century, and has been appreciated for its pharmaceutical potential. In the 18th century, the German polymath Goethe introduced climbers (vine stocks and ivy) to the upper class as part of garden and building art. There is a long experience with indirect façade greening using trellises or pergolas to support vines (e.g. *Vitis vinifera*), and with direct façade greening using plants that have adventitious roots like *Hedera helix* or climbing roots with adhesive pads such as *Parthenocissus tricuspedata*. While vines and climbers have long been associated with building damage and attraction of pests, a detailed study (Schlösser 2003) showed that most inhabitants do have a positive attitude toward façade greening. It remains unclear why façade greening, given its aesthetical value, ecological importance and positive effects on mental and physical health (biophilia), is not more widespread in Europe. One initiative to remedy this is the I-BEST project currently in development by the University of Calabria, Italy: an innovative vegetated module for a green wall, which, by the integration with a rainwater harvesting system, allows for optimal urban water management and provides environmental and thermal benefits from a building scale to a city scale.

Green roofs are as old as façade greening, dating back to the Gardens of Semiramis as well. Traditionally, green roofs took the form of either sloped roofs covered with grass sod, or more sophisticated and intensively used roof gardens (Shafique *et al.* 2018). Turf roofs constructed for their insulation value have been a central feature of vernacular architecture in Iceland (van Hoof & van Dijken 2008), Greenland and Scandinavia (Ahrendt 2007). Roof gardens were constructed in ancient Rome to celebrate luxury, in the Renaissance to demonstrate the humanistic ideas of the owners, in the Baroque to symbolize the artificial look of the garden, and in classicism the antique examples flourished again (Ahrendt 2007). During all these epochs, the roofing technology changed only slightly, with bitumen, lead and copper as the main sealing materials. Apart from the turf roof,

the motivations for hanging gardens have been the need for more productive land in dense cities, and the prestige to own a roof garden which symbolized wealth and power. With the advent of reinforced concrete it became much easier to construct flat roofs, with Hennebique among the first to recognize and to put into practice the greening of flat concrete roofs in 1901 (Kind-Barkauskas *et al.* 2001).

Recently, there is an increasing interest in developing more cost-effective green roof design, to use alternative building materials for liners and substrates, to combine greened roofs with solar energy production, and to create multi-purpose recreational space (Figure 3). Several cities are following this trend, and the EU Research and Innovation policy agenda promotes re-naturing cities and territorial resilience for socially and environmentally responsible communities, through the integration of NBS (EU 2015). However, a city's vision for the promotion and use of green roofs varies with the particularities of each place. Given the sustainability of green roofs over their full life cycle, policies are needed that encourage their use through regulation or financial incentives (such as water or property fee reduction), conditional to a pre-defined sustainable development goal attainment. Setting up quality standards for green roofs is important to scale up this NBS, with the German and the Spanish green roof guidelines being good examples for such (NTJ 11C 2012; FLL 2018).



Figure 3 | Example of cities sharing space with vegetation: Green roof at Praça de Lisboa, Porto, Portugal (photo: Cristina Calheiros).

Larger scale green topics in cities

Historic examples of NBS in city infrastructure are represented through food security systems in cities. There is a long culture of urban allotment gardens in European cities (Bell *et al.* 2016), as well as a history of guidelines that promote food production – for example in Athens, Greece. Here, in the development of the city after the 1960s there were guidelines for front-yards that allowed for the planting of two-three citrus trees, herb gardens and a small vegetable garden. Other examples include cultural landscape sites such as monasteries and cloisters in Europe, where herb gardens, vegetable gardens, orchards, vineyards and seed conservation banks were established and have contributed to food security in European towns for centuries, but also the establishment of cultural landscapes

that protect the sloping banks of water reservoirs from erosion. The role of religious communities in protecting know-how regarding crop modification and soil fertility management practices is significant in Europe, but also around the world. Ancient precedents for integrated aquaculture include the chinampas of Mexico and the integrated rice paddy systems across parts of Asia, while what is today defined as aquaponics may be traced to the lowland Maya, followed by the Aztecs, who raised plants on rafts on the surface of a lake in approximately 1000 AD. Polyculture farming systems are common in far eastern countries as well (<http://www.fao.org/3/y5098e/y5098e06.htm>), as illustrated by the supplementary feeding of carp polycultures fertilized with duck manure in Hong Kong. Another example of historic NBS in infrastructure are the living-root bridges in the northeast Indian state of Meghalaya (Lewin 2012), constructed using the *Ficus elastica* tree and inspiring contemporary architects for techniques called 'baubotanik' (Ludwig 2012). In a similar way, practices of river restoration and bank stabilisation of soil-bioengineering that have been implemented in the rivers and streams of the Alps in Switzerland and Austria for years are being expanded in the design of contemporary ecological rivers and streams in cities.

Bioretention systems, biofilters, raingardens as well as constructed wetlands are green infrastructure systems implemented on the ground level for infiltration of water from different sources such as direct precipitation, runoff water, and in special cases polluted water from combined sewer overflow (CSO). These systems are areas that are excavated and filled with specific media depending on the actual multipurpose functions addressed, which may include maximizing the local infiltration capacity, thereby reducing stormwater volumes and relief pressure from the sewer system, serving as a stand-alone drainage system, supporting vegetation growth and providing sufficient water (Roy-Poirier *et al.* 2010). The last function is of utmost importance, as GI can only provide its benefits when there is sufficient availability of water. An important aspect is thereby related to the pollution of the runoff water. Heavy metals (HM) from roof tops and street runoff can degrade the groundwater quality. To cope with this, filtration media are developed to serve as barriers and retain pollutants such as HM (Haile & Fuerhacker 2018).

CURRENT PRACTICE: CIRCULAR SOLUTION CASE STUDIES

In the following, we present a series of case studies that demonstrate innovative approaches to the development and implementation of NBS in the built environment. The first is a research project on the development of alternative green building materials, and the second is a pilot project demonstrating a novel approach to edible green walls. The third is a multi-faceted experimental park combining a green roof demonstration with a number of other NBS technologies, and the final case study is a built example of a green building site in which the focus is on water-sensitive urban design (WSUD). The tables in the Appendix provide extensive lists of green projects in particular countries, illustrating the scope of implementation of different types of NBS.

Development of biocomposite building materials in the Negev, Israel

Project title: 'Biocomposite Building Materials Based on Agricultural Waste' (Scientific Team: David Pearlmutter, Erez Gal, Yaakov Florentin, Shahar Oannou, Francesca Ugolini)

Location: Sede Boker campus of Ben Gurion University of the Negev, Israel (30°48'N, 34°48'E)

Years of design and construction: 2016–2018

Nature-based solutions services: green building materials, recycled agricultural waste

Biocomposite building materials can have a significantly lower environmental footprint than conventional lightweight concrete, as they incorporate plant-based lightweight aggregates in a protective matrix – and these plants can sequester significant amounts of carbon in their growing phase.

By exploiting agricultural by-products to produce these alternative insulation materials, a further contribution is made towards reducing waste in a circular economy. At the same time, because these plant materials are concealed within an inert binder, they are not exposed to damage from fire, pests or rotting.

Experimental studies in the arid Negev Highlands of southern Israel were conducted to develop and test innovative biocomposite materials incorporating hemp shives and dried orange peels, respectively, as the insulating aggregate. As part of an ongoing life-cycle assessment, the thermal properties of each biocomposite were analyzed through laboratory testing and experiments using small test cells ($1 \times 1 \times 0.6$ m) with 20 cm thick walls.

Functionally graded hemp-lime biocomposite

Hemp-lime (HL) biocomposites are typically non-load bearing wall materials made from the woody core of the hemp plant (a non-psychoactive variety of *Cannabis sativa*), which is dried, cut into ‘shives’ and mixed with a lime binder. These lightweight insulating materials are non-toxic, reusable/recyclable and meet European fire and acoustic standards. Moreover, their production can be carbon ‘negative’, as CO₂ sequestered during the hemp plant’s growth outweighs the net release of carbon in the production of lime (which gradually reabsorbs CO₂ through carbonation). In addition, HL is considered a ‘breathable’ material characterized by moisture buffering and improved indoor air quality. While the outer fibers of the hemp stalk are used for textiles and other products, its woody core comprises about 70% of the plant’s weight and is usually treated as agricultural waste (Ip & Miller 2012; Zampori *et al.* 2013; Florentin *et al.* 2017).

In the first phase of the study, a life-cycle assessment of a homogenous HL biocomposite (450 kg m^{-3}) showed that the net carbon emissions of HL production are drastically reduced relative to a conventional building material with similar density and thermal properties, and that the magnitude of this reduction in embodied carbon is equivalent to about five years’ worth of carbon emitted due to seasonal heating and cooling of a typical building (Florentin *et al.* 2017). The HL was also compared to a material combining internal thermal mass and external thermal insulation, which was better able to moderate the temperature fluctuations of a desert climate. However, because this variable density insulated concrete is based on cement and expanded polystyrene, it is very high in embodied energy and carbon. Thus the second phase of the study focused on the development and analysis of a variable density ‘Gradient Hemp-Lime’ block (Figure 4) which could significantly reduce operational as well as embodied energy and carbon emissions.



Figure 4 | (left) Gradient HL cross section; and (right) gradient HL test cell before plastering and roof installation, with homogenous hemp-lime cast on the corners to prevent thermal bridges. Photos: Y. Florentin.

The optimal configurations for the heavy and light phases of the gradient block were identified through laboratory testing, which included measurements of the density, thermal conductivity and volumetric heat capacity, and compressive strength of a wide range of samples in which various hemp-lime-sand-water ratios were cast and vibrated to separate the layers and attain a density gradient: from heavy on the bottom to light on top. A test cell was built of identical blocks based on the preferred ratio and vibration time, with the heavy side inward.

Results comparing the thermal performance of the gradient HL test cell to that of conventional lightweight concrete (Figure 5) show that during the early fall, the gradient hempcrete preforms better in terms of moderating indoor temperature fluctuations – maintaining a maximum temperature of 23 °C, which is in the range of thermal comfort. Thus the newly developed variable density hemp-lime composite block is seen in a preliminary analysis to offer superior thermal performance when compared with conventional materials of the same thickness. Furthermore, the ‘gradient hemp-lime’ shows considerable potential to substantially reduce the environmental impact of non-load bearing wall materials, especially in terms of CO₂ emissions, due to the carbon-negative bio-based aggregate made from the woody core of the hemp plant. Ongoing work, including a complete life cycle energy and carbon analysis, will provide further evidence of its potential as a sustainable material for the building industry.

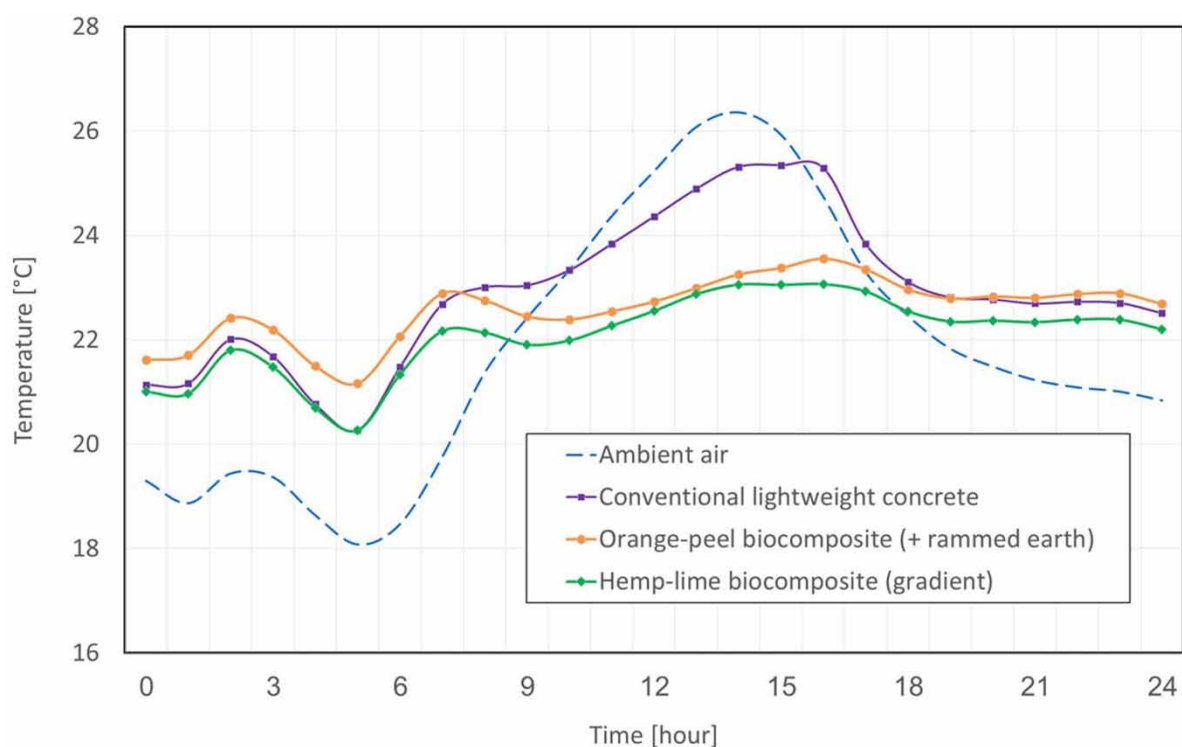


Figure 5 | Internal air temperature of test cells with wall construction based on the gradient hemp-lime and orange-peel biocomposites, compared with conventional lightweight concrete (18 October 2018 at the Sede Boker campus).

Citrus waste bio-composite and rammed earth

An innovative bio-composite building material based on agricultural waste was developed using dried orange peel (OP) particles as a lightweight aggregate and clay as a binder. This insulating biocomposite was integrated in a double-layer wall system, with the inner layer consisting of rammed earth (RE) for thermal mass.

The potential of this green material stems from the fact that most industrial waste from citrus (estimated at 15 million tons per year globally) is created in the juice production process and much of it consists of orange peels (Marín *et al.* 2007; USDA 2014). While this waste material may be used to produce animal feed or natural fertilizer for agriculture (Beccali *et al.* 2009), it is clear that orange peels represent a sizable potential resource for new applications such as building materials. The fact that much of the resource is already concentrated in processing plants for juice production means that its collection could be far more efficient than for other types of agricultural waste. The second wall material, rammed earth, is based on a traditional method of construction with naturally low embodied energy (Venkatarama Reddy & Prasanna Kumar 2010).

In the initial phase of the study, samples of the OP bio-composite with different proportions of OP and clay binder were compared in order to identify the highest proportion of insulating OP that could be used without compromising the mechanical stability of the composite as an infill (non-load bearing) material (Figure 6). The optimal configuration (with a density of 900 kg/m³) was found to contain 46% OP and 52% clay by weight, with the small remainder consisting of Natural Hydraulic Lime (NHL) to minimize shrinkage. This proportion of insulating plant material is in agreement with general recommendations for hemp-lime mixtures as well. OP particle size fractions (from <1.2 to >4.7 mm) and water content were also optimized.



Figure 6 | (left) OP biocomposite samples with varying OP particle size, water content, and binder ratio; (right) test cell walls, with respective 10 cm-thick layers of external orange peel (OP) biocomposite insulation and internal rammed earth (RE) mass, before plastering and roof installation.

Test cell measurements (see Figure 5 above) showed that the orange-peel-rammed earth wall is able to moderate internal temperatures to a greater extent than lightweight concrete, and to nearly the same extent as the graded hemp-lime biocomposite. This indicates that the combination of external biocomposite insulation and internal thermal mass offers pronounced benefits for thermal comfort and energy savings.

Using an Element Analyzer to estimate the amount of carbon sequestered in the plant material, it was found that the carbon concentration (fraction of overall weight) in orange peels is 44%, which is virtually identical to that of hemp shives and similar to that of constituent organic molecules (46% for pectin and 49% for cellulose). This finding is being used for an ongoing life-cycle assessment of OP and HL biocomposites, with indications that both show potential as promising ‘circular solutions’ for the built environment.

Pilot demonstration of an edible green wall in Malmö, Sweden

Project title: Seved Edible green wall

Location: Malmö, Sweden (55°35'N 13°00'E)

Year of design and construction: 2013

Design: Odl i stan/Odlingsnätverket Seved/student från Malmö Högskola using system Gro-Wall

Contractor, installation: Peab (Nordic construction and civil engineering company) together with Peabskolan (a secondary school that trains within the framework of the national high school program building and construction)

Initiator: Föreningen Odlingsnätverket Seved (non-profit organization)

Co-financed: City of Malmö and MKB (*Malmö Kommunala Bostads*), Malmö Planterings- och försköningsförening (Planting and Beautification Association)

Nature-based solutions services: green edible wall, recycled material

Case study by: Alisa Korolova

The Seved Edible green wall in Malmö, Sweden was created in 2013 as a pilot project for the demonstration of vertical community gardens (Figure 7). The main idea was to inspire property owners to use the city space in a new way, as in many areas a lack of space does not allow residents to create community gardens or to grow plants in containers. The wall structure, which has a total area of 50 m² and a maximum height of 5 m, accommodates edible plants throughout the whole year – with specific plant types replaced depending on the season. The ‘summer wall,’ which includes plants such as strawberries, chard, lettuce, celery, spinach and herbs (oregano, lavender or rosemary), is cultivated from May until November. In November the ‘summer wall’ is replaced by the ‘winter wall,’ which is represented mostly by green cabbages and herbs like oregano and thyme. The selection is mainly determined by the visual aesthetics of the plants, with a preference for those that are bushy and compact – while plants that are especially sensitive to wind are generally avoided.



Figure 7 | Seved Edible garden (left); and Seved Edible green wall (right) (photos: Alisa Korolova).

The wall is made up of a modular system called Gro-Wall (<https://www.gro-wall.com.au/>). The system comprises a grid of compartments that are made from felt cloth bags, supplied by Mardam Agentur. The framework for attachment of the bags to the wall is made by Peab, who set up the wall together with the Peabskolan students. The irrigation is handled by an automated drip irrigation system, which is regulated via computer, together with manual watering by a management team from Odlingsnätverket Seved and the local community.

The project contributes to the city of Malmö and its circular economy through multiple ecosystem services: the increase of biodiversity, the safeguarding of edible planting processes, the nurturing of

local residents' relationship to natural food production, the local use and reuse of water that would otherwise be routed to the sewer, and the direct availability of vegetables on the dinner table of local families. It is a demonstration of nature-based solutions at a small scale, with innovative landscape elements designed to enhance circularity in terms of nutrients, food production and water reuse in available open space. More importantly, as a demonstration project it can serve as an example of what is possible for the whole city. In 2014, in fact, Malmö adopted a comprehensive urban farming program to get a better overview of the possibilities and with the aim of further promoting the city gardening concept.

Lessons learned:

- The Gro-Wall system is made of 100% recycled plastic, demonstrating the potential of circular solutions.
- The modular system allows diverse design, and can accommodate the use of vertical space for edible plants all year round.
- Cooperation between land/building owners, professionals and students, together with the engagement of a non-governmental organization (NGO), is a key to successful implementation.
- The project embodies important steps towards social sustainability, by providing support to the local community.

Demonstration of experimental green roof and allied technologies in the 'Urban Hydraulic Park'

Project title: 'Integrated and Sustainable management service for water-energy cycle in urban drainage systems' (Scientific Leader: Patrizia Piro)

Location: Rende, Italy (39°22'N 16°13'E)

Years of design and construction: 2011–2014

Area: The total area of all Experimental Sites located at the Urban Hydraulic Park is more than 700 m²

Design: Urban Hydraulics and Hydrology Laboratory – University of Calabria (Scientific Supervisor Prof. Patrizia Piro) with the cooperation of the companies involved in the Project

Co-financed: Italian National Operative Project (PON) – PON01_02543

Nature-based solutions services: Green roof, Permeable Pavement, Stormwater Filter

Case study by: Patrizia Piro

The 'Urban Hydraulic Park' is an experimental demonstration site located at the University of Calabria, Italy, and specifically in the Vermicelli catchment (27.80 ha) where a series of Nature Based Solutions have been implemented to investigate their efficiency in terms of hydraulic, thermal and environmental benefits. The Park includes a green roof with a rainwater harvesting system, a permeable pavement, a stormwater filter, and a traditional sedimentation tank connected to a treatment unit. It is also equipped with a complex monitoring and acquisition system for the collection of climatic, hydrological, hydraulic, and thermo-physical data in real time.

The green roof experimental site shown in Figure 8 (Piro *et al.* 2019a) is parcelled into four hydraulically independent sectors with an area of about 40–50 m² each: three vegetated roofs and one conventional roof used as reference for the hydraulic and energetic analysis. While the three green roofs differ in terms of their drainage layers and/or the presence of vegetation, they all generally consist (from top to bottom) of a vegetated layer, a soil substrate, a permeable geotextile, a drainage and storage layer, an anti-root layer, and a waterproof membrane. Two sectors were covered by the same native Mediterranean plants (*Carpobrotus edulis*, *Dianthus gratianopolitanus*, and *Cerastium tomentosum*), while the third one hosts colonized plants. The water supply is guaranteed by reusing the green roof's outflow, which is collected in a storage tank (1.5 m³) placed at the base of the building and distributed through a drip irrigation system during drought periods.



Figure 8 | The green roof experimental site at University of Calabria.

As documented in [Palermo *et al.* \(2019\)](#), the green roof described here demonstrated good hydraulic performance in terms of stormwater retention in a Mediterranean climate. By analysing the monitored data collected between October 2015 and September 2016 (62 rainfall events) at an event scale for one of the vegetated sectors, the mean value of subsurface runoff was found to be 32.0% – while the subsurface runoff coefficient, obtained considering stormwater events with precipitation depth of more than 8.0 mm (35 rainfall events), was 50.4%. In addition, the integration of the green roof and rainwater harvesting system implemented in the experimental site provided considerable benefits in terms of rational management of water resources. In this vein, a possible smart optimization of the green roof and rainwater harvesting system was described in [Piro *et al.* \(2019b\)](#).

The permeable pavement experimental site ([Figure 9](#)) was built in a portion of an existing car park. It has an area of around 380 m², divided into two sections: one of about 150 m² with permeable



Figure 9 | The permeable pavement experimental site at University of Calabria.

pavement, and the other left impermeable for use as a reference. It has an average slope of 2%, and a total profile depth of 0.98 m. The surface wear layer consists of porous concrete blocks characterized by high permeability (8 cm depth); while the base layer (35 cm depth); sub-base layer (45 cm depth) and bedding layer (5 cm depth) were defined by following the suggestions of the Interlocking Concrete Pavement Institute (ICPI), which recommends certain ASTM stone gradations. In order to evaluate the hydraulic behaviour of the permeable pavement, a reservoir element model was developed in [Turco *et al.* \(2018\)](#). In this study, the model was calibrated and validated against measured runoff collected on the specific experimental site described here.

Finally, the stormwater filter experimental site ([Figure 10](#)), installed downstream from the permeable pavement, is used to treat stormwater runoff discharged from the adjoining impervious parking lot. It has a surface area of around 125 m², an average slope of 2%, and a total profile depth of 0.75 m, and is covered by a soil substrate vegetated with Mediterranean species. A high permeability geotextile is placed between the soil substrate and the filter layer to prevent fine particles from migrating into the underlying layer. The filter layer is composed of highly permeable gravelly material. Finally, an impervious membrane at the bottom of the profile prevents water percolation into deeper horizons. Based on data collected at the experimental site ([Brunetti *et al.* 2017](#)), the



Figure 10 | The stormwater filter experimental site at University of Calabria.

unsaturated hydraulic properties of the stormwater filter were evaluated and the benefit of surrogate-based modelling was demonstrated in the numerical analysis of sustainable solutions.

Lessons learned:

- Each NBS represents a ‘low impact development’ solution, with a specific stratigraphy designed by taking into account the climate condition and the regulations in force.
- From analysis of the monitoring data, all of these solutions improve urban stormwater management in terms of surface runoff mitigation and water quality enhancement.
- From investigation of energetic data, the green roof proves to be suitable for reducing the temperature variation in the building and mitigating the urban heat island effect.
- The LCA analysis carried out for the specific green roof and permeable pavement confirms the sustainability of these low-impact infrastructures (Maiolo *et al.* 2017).

Photo credits: Urban Hydraulic and Hydrology Laboratory (<http://www.giare.eu/>) – Scientific Supervisor: Patrizia Piro

Zollhallen Platz in Freiburg, Germany

Project title: Zollhallen Platz

Location: Freiburg, Germany (48°0' N/7°50' E)

Year of design: 2009–2010

Year of construction: 2011

Area: 5,600 m²

Design company: Ramboll Studio Dreiseitl

Nature-based solutions services: Water-sensitive urban design, biodiverse local planting, reuse of existing material in new design

Case study by: Dimitra Theochari

Zollhallen Plaza is located at the entrance to a historic train station designated for customs that was restored in 2009 (Figures 11–14). Although the scale of the plaza is small, and it was initially designated to be a simple hardscape area for the new users of this public building, the design team set an ambitious target: to disconnect the plaza from the sewer system, and to create a small-scale urban plaza that would be an example of water-sensitive urban design (WSUD). A series of infiltration points located in the plaza through planters, connected with subsurface gravel trenches and in-built filter medium, are used to reduce the hydraulic overload on the sewer system. The plaza is designed



Figure 11 | Local planting and view to the old train station of Freiburg. The details of the train tracks and the memory of the area is brought back in a system showing applicability of circular city material recycling applications (left), and details of seating designed as being peeled-off the ground to allow for maximizing the space for permeable green surfaces that are entry points to the infiltration system to the underground storage, but also to the groundwater reservoir (right).



Figure 12 | Connecting the hardscape to the green zones, extending the ecology and urban nature qualities of the site.



Figure 13 | Details of planting and the recycled train tracks from the site.



Figure 14 | View of the seating as used by visitors and locals. Area to relax and contemplate urban nature (left); and seating in the green zone and looking out to the city (right). The plaza stormwater system is disconnected from the municipality sewer.

to hold on its surface the volume of water generated by a 20-year, a 50-year and a 100-year rain-event, and to provide flood safety to the city while recharging the ground water table.

In terms of material reuse on site, the rail pieces from the rail yard are reused to structure the inlets of the infiltration with perennials and ornamental grasses, creating an aesthetic appeal of small scape colourful planting. All of the hardscape materials are high-quality demolition materials recycled from the old rail yard, a fact that makes this case study a true example of NBS in circular city principles. In this way, the design evokes the continuity of special historic and cultural features, and the memory of people who worked in the area – contributing further to the social dimension of ecosystem services.

This case study was designed and developed as a real-life project for the city of Freiburg, setting new targets for detaching the plaza from the sewer system and creating a sustainable water irrigation and groundwater infiltration system. Quantitative data on the functioning of the system are not available, but there is common experience from the site and monitoring of the construction quality – as is typical for any city project in the Baden-Württemberg in Germany – that attest to the high efficiency of the system. Qualitatively, the NBS derived from Zollhallen Plaza include an increase in the permeability of the plaza, which does not create a greater burden for the city's stormwater system, and which contributes to the strengthening of the biodiversity of the city of Freiburg through the planting selection. The water circulation and reuse for irrigation of the planting throughout project responds to considerations of NBS in the context of a Circular City.

Lessons learned:

- The hardscape of a small city plaza can be used to create a stormwater management system and extreme flooding management system, independent of the city sewer.
- The project demonstrates circular city applications for material and water that falls on site.
- An on-site water circulation system with an underground storage tank is charged with infiltration through permeable paving.

Photo credits:

Dimitra Theochari

CRITICAL ANALYSIS OF NBS IN THE BUILT ENVIRONMENT

Ecosystem services and disservices

Living vegetation that is integrated with or adjacent to buildings – including green roofs, balconies and façades, as well as gardens, parks and isolated trees – are part of a city's green infrastructure. Despite their urbanized surroundings, these green spaces host a wide range of animal species.

Whether the vegetation is long-established or newly planted, many vertebrates and invertebrates find shelter and food in these areas, including in the soil. Thus, the greening of the built environment contributes to biodiversity by decreasing the impacts of habitat fragmentation in urban ecosystems, and by increasing the permeability of the urban matrix (Martin-Queller *et al.* 2017). This biodiversity also supports a wide range of ecosystem services that contribute to the improvement of human health and wellbeing (Pinho *et al.* 2017).

Urban greening is invaluable for achieving the three main objectives of integrated water management – enhancing water availability, improving water quality and reducing water-related risks (WWAP 2018). Understory plant species contribute to regulating water quality by controlling nutrient runoff (Livesley *et al.* 2016), thus decreasing the resources required to deal with polluted water. Vegetation provides air quality regulation, by preventing pollutants from reaching buildings (Matos *et al.* 2019), thus decreasing the impacts and cost of air pollution in sensitive areas. Local invertebrates contribute to pollination, which together with birds also provide pest regulation (Mexia *et al.* 2018). Green spaces also increase the cultural sense of attachment to the place and to nature, with further benefits to wellbeing (Luz *et al.* 2019).

In addition to providing ecosystem services, however, the establishment and restoration of planted areas in the midst of buildings may increase the exposure of residents to allergenic material, mostly from vegetation pollen. A list of allergenicity of common tree species is available, and should be taken into account when building or restoring urban green spaces (Carriñanos *et al.* 2019). High vegetation density, although a bonus for biodiversity, may increase some people's sense of insecurity, and thus should be evaluated for each case. High moisture, promoted by excessive watering, may cause an increase in local pest populations.

However, balanced urban ecosystems – most notably those in which the use of insecticides is limited – are likely to mitigate this effect by increasing the local populations of insect parasites or predators, such as birds or other insects (Sanchez-Bayo & Wyckhuys 2019). Planting trees near air pollution sources will increase the local deposition of pollutants (Santos *et al.* 2017), screening them from the urban air to which urban residents are exposed. While this may benefit those located beyond the trees, however, it may also increase pollution loads for those located between the air pollution source and the trees. Although such trade-offs may have no measurable effect on the average air pollution status in the city, careful planning must take them into account in order to provide the highest air quality where it is needed most.

Other planning and management options also influence the ecosystem services provided by urban green infrastructure, because the same choice of habitat (e.g. grass vs forest) cannot maximize all ecosystem services. For example, native vegetation can provide many support and regulation ecosystem services, such air and microclimate regulation, due to a more complex vegetation structure (Vieira *et al.* 2018). However, other services such as pollination are not favoured by such dense vegetation (Mexia *et al.* 2018) due to the exclusion of some birds' functional types. Additionally, vegetation density is not related to people's willingness to visit parks, highlighting that cultural services are not necessarily increased in areas where support and regulation ecosystem services are the highest (Shanahan *et al.* 2015).

Implementation of NBS for a resourceful circular city: the role of EU policy and international policy drivers

Through its general environmental legislation, the EU has policies in place to promote nature-based solutions in European cities. These policies aim to ensure that urban residents can enjoy clean air and water and avoid excessive exposure to noise, and that cities deal properly with waste, protect nature and biodiversity, and promote green infrastructure. The European Green Capital (http://ec.europa.eu/environment/europeangreencapital/index_en.htm) and European Green Leaf (<http://ec.europa.eu/environment/europeangreencapital/europeangreenleaf/index.html>) Award programs

are tangible initiatives which allow cities to showcase their environmental performance, and policy instruments such as the Circular Economy Action Plan (http://ec.europa.eu/environment/circular-economy/index_en.htm) even address issues such as resource efficiency and raw materials – which can find application in construction, as well as other sectors.

The EU has also elaborated a vision on how to build a sustainable finance strategy (https://ec.europa.eu/info/business-economy-euro/banking-and-finance/sustainable-finance_en) that can cope with the economic challenges of implementing NBS. With an emphasis on funding society's long-term needs, the goal is to strengthen financial stability by incorporating environmental, social and governance (ESG) factors into investment decision-making. Tangible actions include establishing an EU classification system for sustainable activities, creating standards and labels for green financial products, and fostering investment in sustainable projects.

By adopting the Paris Agreement on climate change and the UN 2030 Agenda for Sustainable Development in 2015, governments from Europe and around the world agreed on a more sustainable and resilient path for our planet, providing environmental, social and economic benefits for all. Better alignment of their agendas on sustainable development could unlock the mechanisms needed to achieve a coordinated perspective, utilizing NBS as a cost-effective way of creating greener, more sustainable and more competitive circular economies.

However, the EU still needs a tighter focus on nature-based solutions that are targeted directly to green building materials, systems and sites. The main legislative instrument dedicated specifically to buildings is the 2010 Energy Performance of Buildings Directive (EPBD), which like the 2012 Energy Efficiency Directive focuses exclusively on operational energy – and as such, does not cover the overall life cycle impacts of buildings that are crucial to any vision of a circular economy. The intent of achieving 'circular buildings' is to comprehensively reduce life cycle impacts, and at the same time provide healthy and comfortable spaces for urban dwellers.

This sort of holistic approach to circularity is still lacking in existing certification systems, though minimum requirements for circular design are in fact part of an EU 2017 framework called Level(s), whose development is ongoing.

The lack of integration between NBS and building-related policy is illustrated by an emphasis on design strategies and products which save energy in a building's operation but have high levels of embodied energy and carbon in their production. For example, the shading of windows to prevent overheating is an operationally energy-efficient strategy, but one which is typically implemented using elements such as roller shutters made from materials like aluminium or other metals and plastics which are energy-intensive in their production. Alternatively, systems that use live plants for shading can reduce the building's environmental footprint in a more holistic manner – but they have yet to be mainstreamed in practice or prioritized in policy. In general, the greening of built surfaces – through the use of plant-based building materials, green roofs and walls, and water-sensitive site design – is still not sufficiently promoted.

CONCLUSIONS: ADVANCING THE IMPLEMENTATION OF NBS IN THE BUILT ENVIRONMENT

In light of the preceding discussion, we may ask why there are no specific EU policies, whether in the form of regulations, incentives, or educational tools, that explicitly promote NBS in the built urban environment. One question to be addressed regards the legal obstacles: once appropriate green technologies are available, specific policies need to be formulated in order to provide a regulatory framework that will allow these alternative approaches to find application in the construction sector, which is very strictly regulated (<https://www.cen.eu/Pages/default.aspx>). Part of this policy formulation involves the definition not just of technical measures, but of long-term criteria and aims that are aligned with the transition to a circular economy.

If the problem is a lack of information and precedents, then the review of case studies presented above may be seen as a step forward in providing such information. Overall, these case studies demonstrate that existing and developing nature-based solutions in the built environment are indeed effective and promising. We would argue that it is the implementation of these existing approaches that is firstly lacking, and this alone would hold great benefits in terms of sustainable and resilient development. In addition, further research is needed into the technical and societal aspects of these solutions to make them more powerful and appropriate for our future cities.

To the extent that a limiting factor is represented by a lack of technical data and adeptness with appropriate tools, there are existing sustainability indicators that can be leveraged. These include Life-Cycle Assessment (LCA), Material Flow Analysis (MFA), and many other metrics that address circular flow of energy, water and materials in a life cycle perspective. Undoubtedly there is still a need for R&D on design tools that are scientifically robust and at the same time accessible to designers and consultants. Among other things, better definitions of minimum performance levels, multiple functions, and valorisation of side effects should be included in decision making systems regarding the implementation of NBS in the built environment.

Further research into building-related NBS thus needs to be prioritized. The indicative case studies presented here suggest that funding for further pilot studies, demonstrations, and experimental monitoring data is crucial. Systematic analysis of the performance of NBS needs to be conducted with reference to conventional technical systems, so that the relative benefits may be quantified. Cost-benefit analysis of NBS against other solutions can only be done in a case-by-case analysis, but an emerging pattern when evaluating the success of NBS is that it must: (1) involve a large number of stakeholders and their interests; and (2) be shown to be a sustainable solution not only ecologically, but economical and socially as well (Nesshover *et al.* 2017).

We may also draw specific conclusion regarding the three levels of the built environment addressed in this paper: green building materials, systems and sites.

- *Regarding green building materials:* We emphasize that in contrast to the vernacular, modern construction is largely based on manufactured materials that offer reliability and convenience – but that these properties are usually attained through high-temperature, resource-intensive processes that generate considerable waste and atmospheric emissions. Biocomposite materials, which draw on the environmental benefits of nature-based ingredients but also fulfil the required attributes of modern construction thanks to their protective matrix, can make a significant contribution in the transition to a circular economy. A holistic life-cycle analysis can help to identify the sustainability potential and weak-points of such solutions.
- *Regarding green building systems:* A huge variety of building greening systems are already marketed, all promising to mitigate negative impacts of built environments. However, they come with different environmental, economic and social costs, onsite and offsite – ‘green’ does not mandatorily mean ‘sustainable’. The integration of circular economy approaches can improve building greening systems’ efficiency, sufficiency and consistency. Prior to investing tax money in NBS it will be crucial to prioritize these systems regarding their ecological, economic and social impacts using holistic life-cycle analyses. LCAs can be used to identify both optimization potentials and best practices. In order to conduct them in a reproducible and transparent way, a harmonised set of a-priori weighted assessment criteria has to be employed and clearly documented.
- *Regarding green building sites:* Especially at the scale of semi-public and public open spaces, the effective integration of NBS can meaningfully contribute to resolving larger scale societal challenges locally, by making cities more healthy and inclusive as well as more resource-efficient. In particular, urban food production can support action toward urban resilience and social cohesion. Water-sensitive urban design approaches and a shift from conventional ‘grey’ infrastructure to blue-green infrastructure solutions offer flood safety, resilience and opportunities to close the water cycle on every site. Moreover, green

building sites contribute in terms of noise mitigation, biodiversity connectivity, microclimate mitigation and outdoor comfort, while often their benefits are multiple and overlapping, including these and many more ecosystem services. It should be noted that the green building sites are also the designated areas where the offset of the carbon footprint of the development can be placed.

Finally, it is crucial to see green building materials, systems and sites as part of a holistic urban web. When different types of NBS are combined in an integral way – creating a multi-scale network of urban blue-green infrastructure – then the paradigm shift toward circularity will indeed be on its way.

ACKNOWLEDGEMENTS

The work is funded within the COST Action CA17133 Circular City ('Implementing nature based solutions for creating a resourceful circular city', <http://www.circular-city.eu>, duration 22 October 2018–21 October 2022). COST Actions are funded within the EU Horizon 2020 Programme. The authors are grateful for the support. Ramboll Studio Dreiseitl for the Zollhallen Plaza case study. The 'Urban Hydraulic Park' Demonstration site was funded by the Italian Operational Project (PON) – Research and Competitiveness for the convergence regions 2007/2013 – I Axis 'Support to structural changes' operative objective 4.1.1.1. 'Scientific-technological generators of transformation processes of the productive system and creation of new sectors' Action II: 'Interventions to support industrial research'. The 'I-Best' Project (Scientific Leader Prof. Mario Maiolo) is funded by Italian National Operational Program 'Enterprise and Competitiveness' 2014–2020 ERDF – I AXIS 'Innovation' - Action 1.1.3 – 'Support for the economic enhancement of innovation through experimentation and the adoption of innovative solutions in processes, products and organizational formulas, as well as through the financing of the industrialization of research results'.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this paper is available at <http://dx.doi.org/10.2166/bgs.2019.928>.

REFERENCES

- Ahrendt, J. 2007 *HISTORISCHE GRÜNDÄCHER: Ihr Entwicklungsgang bis zur Erfindung des Eisenbetons, Teil I. Dissertation* (PhD Thesis), Technische Universität Berlin, German. online: urn:nbn:de:kobv:83-opus-14771.
- Beccali, M., Cellura, M., Iudicello, M. & Mistretta, M. 2009 *Resource consumption and environmental impacts of the agrofood sector: life cycle assessment of Italian citrus-based products. Environmental Management* **43** (4), 707–724.
- Bell, S., Fox-kämper, R., Keshavarz, N., Benson, M. & Caputo, S. 2016 Urban Allotment Gardens in Europe – 9 March 2016.
- Blaser, W. 1982 *Elementare Bauformen: Quellen moderner Architektur (Elemental Building Forms: Sources of Modern Architecture)*. Beton-Verlag GmbH, Duesseldorf, Germany.
- Brown, A. 2012 *Just Enough: Lessons in Living Green From Traditional Japan*. Tuttle Publishing, North Clarendon, VT, USA.
- Browning, W. D., Ryan, C. O. & Clancy, J. O. 2014 *14 Patterns of Biophilic Design*. Terrapin Bright Green, LLC, New York.
- Brunetti, G., Šimůnek, J., Turco, M. & Piro, P. 2017 *On the use of surrogate-based modeling for the numerical analysis of low impact development techniques. Journal of Hydrology* **548**, 263–277.
- Buchin, O., Hoelscher, M., Nehls, T. & Ziegler, F. 2016 *Evaluation of the health-risk reduction potential of countermeasures to urban heat islands. Energy and Buildings* **114**, 27–37.
- Cariñanos, P., Grilo, F., Pinho, P., Casares-Porcel, M., Branquinho, C., Acil, N., Andreucci, M. B., Anjos, A., Bianco, P. M., Brini, S., Calaza-Martínez, P., Calvo, E., Carrari, E., Castro, J., Chiesura, A., Correia, O., Gonçalves, A., Gonçalves, P., Mexia, T., Mirabile, M., Paoletti, E., Santos-Reis, M., Semenzato, P. & Vilhar, U. 2019 *Estimation of the allergenic potential of urban trees and urban parks: towards the healthy design of urban green spaces of the future. International Journal of Environmental Research and Public Health* **16** (8), 1357.
- Elmqvist, T., Fragkias, M., Goodness, J., Güneralp, B., Marcotullio, P. J., McDonald, R. I., Parnell, S., Schewenius, M., Sendstad, M., Seto, K. C. & Wilkinson, C. (eds) 2013 *Urbanization, Biodiversity and Ecosystem Services: Challenges and*

- Opportunities. A Global Assessment A Part of the Cities and Biodiversity Outlook Project.* Springer, Dordrecht, Heidelberg, New York, London.
- Enerdata 2012 *Energy Efficiency Trends in Buildings in the EU: Lessons From the ODYSSEE MURE Project.* https://energiatagud.ee/img_auth.php/6/68/Enerdata_Energy_Efficiency_Trends_in_Buildings_in_the_EU_2012.pdf (accessed 30 May 2019).
- European Union 2015 *Towards an EU Research and Innovation Policy Agenda for Nature-Based Solutions & Re-Naturing Cities Final Report of the Horizon 2020 Expert Group on Nature-Based Solutions and Re-Naturing Cities.*
- FLL 2018 *Green Roof Guidelines – Guidelines for the Planning, Construction and Maintenance of Green Roofs*, 2018 edn. Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V. (FLL), Bonn.
- Florentin, Y., Pearlmutter, D., Givoni, B. & Gal, E. 2017 *A life-cycle energy and carbon analysis of hemp-lime biocomposite building materials.* *Energy and Buildings* **156**, 293–305.
- Georgi-Thomas, A. & Zeumer, M. 2012 Einfach nachhaltig (Simply Sustainable). In: *Im Detail: Einfach Bauen Zwei: nachhaltig, kostengünstig, lokal (In Detail: Simply Building Two: Sustainable, Economical, Local)* (Schittich, C., ed.). Institut für internationale Architektur-Dokumentation GmbH & Co. KG, Postfach 201054, D-80010, Muenchen, Germany, pp. 42–49.
- Gothein, M. L. 1926 *Geschichte der Gartenkunst 1: Von Aegypten bis zur Renaissance in Italien, Spanien und Portugal (History of Garden Art 1: From Egypt to the Renaissance of Italy, Spain and Portugal)* (Diedrichs, J., ed.).
- Haile, T. M. & Fuerhacker, M. 2018 *Simultaneous adsorption of heavy metals from roadway stormwater runoff using different filter media in column studies.* *Water* **10** (9), 160.
- Heringer, A. 2012 Einfach lokal (Simply Local). In: *Im Detail: Einfach Bauen Zwei: nachhaltig, kostengünstig, lokal (In Detail: Simply Building Two: Sustainable, Economical, Local)* (Schittich, C., ed.). Institut für internationale Architektur-Dokumentation GmbH & Co. KG, Postfach 201054, D-80010, Muenchen, Germany, pp. 50–55.
- Huberman, N., Pearlmutter, D., Gal, E. & Meir, I. A. 2015 *Optimizing structural roof form for life-cycle energy efficiency.* *Energy and Buildings* **104**, 336–349.
- Ip, K. & Miller, A. 2012 *Life cycle greenhouse gas emissions of hemp-lime wall constructions in the UK.* *Resources, Conservation and Recycling* **69**, 1–9.
- IUCN Commission on Ecosystem Management 2019 *Nature-based Solutions.* <https://www.iucn.org/commissions/commission-ecosystem-management/our-work/nature-based-solutions> (accessed 30 May 2019).
- Jernelöv, A. 2017 Dutch Elm Disease in Europe and North America. In: *The Long-Term Fate of Invasive Species.* Springer, Cham, pp. 161–176.
- Kabisch, N., Korn, H. & Stadler, J. (eds) 2017 *Nature-Based Solutions to Climate Change Adaptation in Urban Areas Linkages Between Science, Policy and Practice* (Bonn, A., ed.). Springer. doi:10.1007/978-3-319-56091-5.
- Kind-Barkauskas, F., Kauhsen, B., Polónyi, S. & Brandt, J. 2001 *Beton Atlas.* Detail, Berlin, p. 298.
- Langergraber, G., Pucher, B., Simperler, L., Kisser, J., Katsou, E., Buehler, D., Garcia Mateo, M. C. & Atanasova, N. 2019 *Implementing Nature-Based Solutions for Creating A Resourceful Circular City* (submitted). *Blue-Green Systems.*
- Lehner, E. 2016 *Roots of Architecture: Building Traditions in Non-European Cultures.* IVA-ICRA Publishing, Institute for Comparative Architecture, Vienna, Austria.
- Lewin, B. 2012 *India's Living Bridges.* Reader's Digest Australia, pp. 82–89. Archived from the original on 16 November 2012.
- Livesley, S. J., Ossola, A., Threlfall, C. G., Hahs, A. K. & Williams, N. S. G. 2016 *Soil carbon and carbon/nitrogen ratio change under tree canopy, tall grass, and turf grass areas of urban green space.* *Journal of Environmental Quality* **45**, 215–223.
- Ludwig, F. 2012 Baubotanik Tower. In: *Bio Design: Nature + Science + Creativity* (Myers, W., ed.). The Museum of Modern Art, New York, p. 304.
- Luz, A., Buijs, M., Aleixo, C., Metelo, I., Grilo, F., Branquinho, C., Santos-Reis, M. & Pinho, P. 2019 *Should I stay or should I go? modelling the fluxes of urban residents to visit green spaces.* *Urban Forestry & Urban Greening* **40**, 195–203.
- Maiolo, M., Carini, M., Capano, G. & Piro, P. 2017 *Synthetic sustainability index (SSI) based on life cycle assessment approach of low impact development in the Mediterranean area.* *Cogent Engineering* **4** (1), 1410272. <https://doi.org/10.1080/23311916.2017.1410272>.
- Marín, F. R., Soler-Rivas, C., Benavente-García, O., Castillo, J. & Perez-Alvarez, J. A. 2007 *By-products from different citrus processes as a source of customized functional fibres.* *Food Chemistry* **100** (2), 736–741.
- Martin-Queller, E., Albert, C. H., Dumas, P. J. & Saatkamp, A. 2017 *Islands, mainland, and terrestrial fragments: how isolation shapes plant diversity.* *Ecology and Evolution* **7**, 6904–6917.
- Matos, P., Vieira, J., Rocha, B., Branquinho, C. & Pinho, P. 2019 *Modeling the provision of air-quality regulation ecosystem service provided by urban green spaces using lichens as ecological indicators.* *Science of the Total Environment* **665**, 521–530.
- Mexia, T., Vieira, J., Principe, A., Anjos, A., Silva, P., Lopes, N., Freitas, C., Santos-Reis, M., Correia, O., Branquinho, C. & Pinho, P. 2018 *Ecosystem services: urban parks under a magnifying glass.* *Environmental Research* **160**, 469–478.
- Nesshover, C., Assmuth, T., Irvine, K. N., Rusch, G. M., Waylen, K. A., Delbaere, B., Haase, D., Jones-Walters, L., Keune, H., Kovacs, E., Krauze, K., Külvik, M., Rey, F., Dijk, J., Vistad, O. I., Wilkinson, M. E. & Wittmer, H. 2017 *The science, policy and practice of nature-based solutions: an interdisciplinary perspective.* *Science of the Total Environment* **579**, 1215–1227.
- NTJ 11C 2012 *Normas Técnicas de jardinería y paisajismo - A Jardinamientos especiales: cubiertas verdes.* Fundació de la Jardineria i el Paisatge.
- Olmsted, Frederick Law 1865 *Introduction to Yosemite and the Mariposa Grove: A Preliminary Report.*
- O'Sullivan, O. S., Holt, A. R., Warren, P. H. & Evans, K. L. 2017 *Optimising UK urban road verge contributions to biodiversity and ecosystem services with cost-effective management.* *Journal of Environmental Management* **191**, 162–171.

- Palermo, S. A., Turco, M., Principato, F. & Piro, P. 2019 Hydrological effectiveness of an extensive green roof in Mediterranean climate. *Water* **11** (7), 1378.
- Pearlmutter, D. 2007 Architecture and climate: the environmental continuum. *Geography Compass* **1** (4), 752–778.
- Pinho, P., Moretti, M., Luz, A. C., Grilo, F., Vieira, J., Luís, L., Rosalino, L. J., Martins-Loução, M. A., Santos-Reis, M., Correia, O., Garcia-Pereira, P., Gonçalves, P., Matos, P., de Carvalho, R. C., Rebelo, R., Dias, T., Mexia, T. & Branquinho, C. 2017 Biodiversity as Support for Ecosystem Services and Human Wellbeing. In: *The Urban Forest: Cultivating Green Infrastructure for People and the Environment* (Pearlmutter, D., Calfapietra, C., Samson, R., O'Brien, L., Krajter Ostoić, S., Sanesi, G. & Alonso del Amo, R., eds). Springer, Cham. Future City **7**, pp. 67–78.
- Piro, P., Carbone, M., Morimanno, F. & Palermo, S. A. 2019a Simple flowmeter device for LID systems: from laboratory procedure to full-scale implementation. *Flow Measurement and Instrumentation* **65**, 240–249.
- Piro, P., Turco, M., Palermo, S. A., Principato, F. & Brunetti, G. 2019b A Comprehensive Approach to Stormwater Management Problems in the Next Generation Drainage Networks. In: *The Internet of Things for Smart Urban Ecosystems* (Piro, P., ed.). Springer, Cham, pp. 275–304.
- Prieto-Sandoval, V., Jaca, C. & Ormazabal, M. 2018 Towards a consensus on the circular economy. *Journal of Cleaner Production* **179**, 605–615.
- Rodgers, P. 2019 The Living Root Bridge Project: A Database for Tribal Botanical Architecture. <https://livingrootbridges.com/about/> (accessed 30 May 2019).
- Roy-Poirier, A., Champagne, P. & Fillion, Y. 2010 Review of bioretention system research and design: past, present, and future. *Journal of Environmental Engineering* **136**, 9.
- Saaroni, H., Amorim, J. H., Hiemstra, J. A. & Pearlmutter, D. 2018 Urban green infrastructure as a tool for urban heat mitigation: survey of research methodologies and findings across different climatic regions. *Urban Climate* **24**, 94–110.
- Sanchez-Bayo, F. & Wyckhuys, K. A. G. 2019 Worldwide decline of the entomofauna: a review of its drivers. *Biological Conservation* **232**, 8–27.
- Santos, A., Pinho, P., Munzi, S., Botelho, M. J., Palma-Oliveira, J. M. & Branquinho, C. 2017 The role of forest in mitigating the impact of atmospheric dust pollution in a mixed landscape. *Environmental Science and Pollution Research* **24**, 12038–12048.
- Sauer, C. 2012 Einfach konstruieren (Simply constructed). In: *Im Detail: Einfach Bauen Zwei: nachhaltig, kostengünstig, lokal (In Detail: Simple Building Two: Sustainable, Economical, Local)* (Schittich, C., ed.). Institut für internationale Architektur-Dokumentation GmbH & Co. KG, Postfach 201054, D-80010, München, Germany, pp. 12–23.
- Schlösser, S. 2003 Zurakzeptanz von Fassadenbegrünungen. *Meinungsbilderkölnbürger – einebevölkerungsumfrage*. PhD, Univ. Köln, p. 184.
- Schmitt, U., Luer, B., Dujesiefken, D. & Koch, G. 2014 The massaria disease of plane trees: its wood decay mechanism. *IAWA Journal* **35** (4), 395–406.
- SenUVK 2019 Senate Department for Environment, Transportation and Climate Protection. Bestandszahlen zu Strassenbäumen. https://www.berlin.de/senuvk/umwelt/stadtgruen/stadtbaeume/de/daten_fakten/uebersichten/index.shtml (accessed 1 November 2019).
- Shafique, M., Kim, R. & Rafiq, M. 2018 Green roof benefits, opportunities and challenges – A review. *Renewable and Sustainable Energy Reviews* **90**, 757–773.
- Shanahan, D. F., Lin, B. B., Gaston, K. J., Bush, R. & Fuller, R. A. 2015 What is the role of trees and remnant vegetation in attracting people to urban parks? *Landscape Ecology* **30**, 153–165.
- Turco, M., Brunetti, G., Carbone, M. & Piro, P. 2018 Modelling the hydraulic behaviour of permeable pavements through a reservoir element model. *International Multidisciplinary Scientific GeoConference on SGEM: Surveying Geology & Mining Ecology Management* **18**, 507–514.
- Turner, W. 1538 *Libellus de re Herbaria Novus*. <https://doi.org/10.5962/bhl.title.59358> (accessed 30 May 2019)
- USDA 2014 *Citrus: World Markets and Trades*. United States Department of Agriculture. Retrieved from <http://www.fas.usda.gov/data/citrus-world-markets-and-trade> (accessed 30 May 2019).
- US Energy Information Administration 2017 International Energy Outlook 2017. <https://www.eia.gov/outlooks/archive/ieo17/> (accessed 30 May 2019).
- van Hoof, J. & van Dijken, F. 2008 The historical turf farms of Iceland: architecture, building technology and the indoor environment. *Building and Environment* **43** (6), 1023–1030.
- Venkatarama Reddy, B. V. & Prasanna Kumar, P. 2010 Embodied energy in cement stabilised rammed earth walls. *Energy and Buildings* **42**, 380–385.
- Vieira, J., Matos, P., Mexia, T., Silva, P., Lopes, N., Freitas, C., Correia, O., Santos-Reis, M., Branquinho, C. & Pinho, P. 2018 Green spaces are not all the same for the provision of air purification and climate regulation services: the case of urban parks. *Environmental Research* **160**, 306–313.
- Wieland, D. 1983 Topographie. Bauen und Bewahren: der Hausbaum. Bayerischer Rundfunk (German) <https://www.br.de/mediathek/video/topographie-1983-der-hausbaum-av:5896bbf2ab0d0d0012fcd4f5> (accessed 30 May 2019).
- WWAP (United Nations World Water Assessment Programme)/UN-Water 2018 *The United Nations World Water Development Report 2018: Nature-Based Solutions for Water*. UNESCO, Paris.
- Zampori, L., Dotelli, G. & Vernelli, V. 2013 Life cycle assessment of hemp cultivation and use of hemp-based thermal insulator materials in buildings. *Environmental Science and Technology* **47** (13), 7413–7420.

First received 27 June 2019; accepted in revised form 11 November 2019. Available online 3 December 2019